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Nitrogen cycling assessment in a hedgerow intercropping system using ^{15}N enrichment

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Abstract

Nitrogen (N) cycling was determined in monocultures of *Sorghum bicolor* (L.) Moench and alley cropped sorghum with *Acacia saligna* (Labill.) H. Wendl. in semiarid Northern Kenya. N input through biological N_2 fixation of the acacia, N transfer from the legume to the intercrop and losses of applied N through harvest and leaching were estimated using ^{15}N enrichment. The biological N_2 fixation and N transfer estimates clearly demonstrated the limitations of ^{15}N enrichment techniques in field experiments showing even higher transfer than actually fixed N. Therefore, N transfer in the hedgerow intercropping system could not be determined by the ^{15}N dilution methodology. The ^{15}N balance approach, however, yielded reliable results even 1.5 years after ^{15}N application. 74 to 88% of the applied ^{15}N was recovered after three cropping cycles, most of it in the soil (0–1.2 m). Only about 10% of the ^{15}N was taken up by the above-ground vegetation of both monoculture and agroforestry. The trees took up more of the applied ^{15}N (8.4%) than the sorghum (1.3%) in the agroforestry system, indicating nutrient competition between tree and crop. Leaching losses below 1.2 m depth were low in this semi-arid environment with 3 and 6% of the applied ^{15}N in the monoculture and agroforestry system, respectively. ^{15}N losses from leaching were 2.5 times higher in the alley than under the tree row. Incorporating the leguminous tree into the sorghum cropping system had no effect on total leaching and total uptake of applied ^{15}N in above-ground biomass.

Introduction

Nitrogen is one of the most important nutrients limiting crop production in tropical smallholder agriculture (Sanchez 1976). Whereas numerous studies exist about N management in humid areas, information about N cycling in dryland agriculture is scarce (Vlek et al. 1981).

Integrating leguminous trees into farmland may improve the N supply of the cropping system through biological N_2 fixation (Dakora and Keya 1997). Higher crop yields, however, can only be achieved if the fixed N can actually be utilized by the annual crop planted between the trees. Some information about the effects of mulched tree prunings on intercrop performance in alley cropping systems is available (Palm 1995), but the below-ground N fluxes and interactions between trees and crops have not been sufficiently addressed up to now.

In addition to increasing the N input, N losses must also be minimized to improve the N benefit to the crop. It has been frequently hypothesized that trees reduce nutrient leaching and form a safety-net under the root zone of the annual intercrop (e.g. Van Noordwijk et al. (1996)). Strong evidence exists that trees are able to reduce nutrient leaching in comparison to sole cropped annuals (Hartemink et al. 1996; Seyfried and Rao 1991). How leguminous trees affect N cycling in simultaneous tree-crop associations is less clear. Agroforestry systems may have enhanced nutrient cycling compared to monocultures (Schroth 1995), but experimental evidence still needs to be gathered.

In the following experiment, we studied (i) the amount and dynamics of the N input from biological N_2 fixation, (ii) the lateral distribution of the N input between tree and crop, and (iii) the output of applied ^{15}N by leaching in an hedgerow intercropping system during three vegetation periods.

Material and methods

Study site and experimental setup

The present study was carried out on a calcareous Fluvisol (FAO 1990) in the dry tropical savanna of Northern Kenya at an altitude of 620 m a.s.l. between 1994 and 1996. The soils were sandy to clayey loams with high pH (8.2) and low organic carbon (5.3 g kg^{-1}) and N contents (0.42 gkg^{-1}). Mean annual precipitation was 318 mm (from 14 years; W. I. Powell, and Turkana Drought Control Unit, unpubl. data), 309 and 330 mm in 1995 and 1996, respectively (Figure 1). The experiments were conducted in a runoff irrigation system as described by Lehmann et al. (1998a). After heavy storms, runoff water was guided into cropped fields, which received up to 500 mm with each rainfall event in April/May, August and November 1994, in May and September 1995 and in April and August 1996. After the water had infiltrated, the crops entirely relied on the stored soil moisture. After the flood in November 1994, *Acacia saligna* (Labill.) H. Wendl. was planted in hedgerows 4 m apart from each other with 1 m distance between the trees within a row (2500 trees ha^{-1}) in three replicates. Five hedges were planted in each plot with 14 trees per row. Only the central 30 trees were used for sampling, leaving a distance of 8 m to the adjacent plots. The saplings were inoculated with a mixture of 9 strains of Rhizobium spp. commonly found in the area (Kenya Forestry Research Institute KEFRI). This study is part of a larger experiment (Lehmann et al. 1998a), and here only intercropped trees with *Sorghum bicolor* (L.) Moench were compared with a sorghum monoculture.

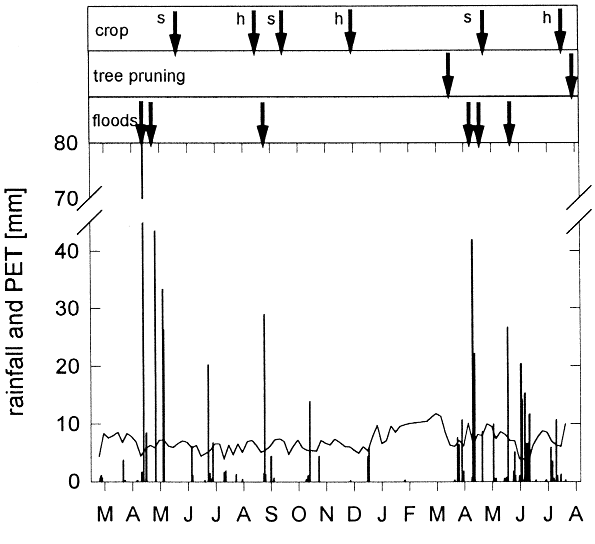

Figure 1. Rainfall distribution (bars), potential evapotranspiration (line) (Droppelmann 1999), crop sowing (s) and harvest (h), pruning and floods from March 1995 to August 1996.

In March and August 1996, the trees were pruned to a height of 1.5 m, and the prunings were separated into leaves and branches and then weighed. Sorghum was sown in rows 0.5 m apart with 0.25 m distance between plants in the row in June and September 1995 and in May 1996 (Figure 1). In the agroforestry plots, every 8th crop row was replaced by a tree row. Six to 12 randomly chosen stands per treatment were harvested 90 days after planting and weighed. All harvested biomass was taken out of the system.

Tracer application

^{15}N was applied as $(NH_4)_2SO_4$ with 10 atom % ^{15}N excess at a rate of 10 kg N ha^{-1} before the first flood in March 1995. Solution containing the tracer was injected at 0.05 m depth in a grid of 0.15 m to prevent wind erosion from removing the ^{15}N. The tracer was applied in subplots of 6 × 8 m in the agroforestry system and 4 × 4 m in the sorghum monoculture. The microplots were surrounded by iron sheets (0.3 m above, 0.2 m below the soil surface with an opening for irrigation) to minimize above-ground lateral transport of the ^{15}N by the runoff water during irrigation.

Determination of biological N_2 fixation and transfer

The biological N_2 fixation was measured in the agroforestry system using the ^{15}N dilution method

(Chalk 1985). The stable N isotope composition was compared in leaves and branches of the *Acacia* and a non-N_2-fixing reference tree, which was planted in each replicate at the same time as the acacia. The standard requirement for application of the isotope dilution method is that the same ^{15}N enrichment must exist in the soil N source for plant uptake by both the legume and non-legume (Witty 1983). Therefore, the ^{15}N enrichment of the mineral soil N pool and the mineral N uptake by the legume and the reference tree should have the same temporal and spatial patterns. Since these preconditions are not easily obtainable the following two criteria were used: (i) a similar above-ground N uptake and (ii) a similar rooting pattern of the legume and the reference tree. To test for similar above-ground N accumulation, two tree species were grown in the experimental plots, *Cordia sinensis* (Lam.) and *Senna siamea* (syn. *Cassia siamea* (Lam.)). Visually, *Senna* matched the growth of the *Acacia* best and was therefore examined further. Additionally, Ladha et al. (1993) could demonstrate that *Senna* ssp did not fix atmospheric N_2 on an acid Haplorthox in the Philippines; we assumed that this also held for our site. To test for similar below-ground growth the root distributions of *Acacia* and *Senna* were compared in March 1996 using destructive root sampling as described by Lehmann and Zech (1998). The root length density of *Acacia saligna* and *Senna siamea* was determined in the tree row to a depth of 0.9 m in 0.3 m depth increments using four composite samples per tree in three replicates. The above-ground biomass of *Senna* was determined as described for the acacia. The biological N_2 fixation of leaves and branches was calculated using the following equations for the proportion of N derived from the atmosphere (%Ndfa):

$$\%Ndfa = \left(1 - \frac{atom\%N^{15}excess_{leg}}{atom\%N^{15}excess_{nonleg}}\right) \times 100 \quad (1)$$

with leg denoting the legume and nonleg the non-N_2-fixing reference tree. Together with the total amount of N (N_{tot}) in the plant we obtained the total N derived from N_2 fixation (Ndfa):

$$Ndfa = N_{tot} \times \frac{\%Ndfa}{100} \quad (2)$$

The proportion of sorghum N derived from transfer (%Ndft) from the *Acacia* to the sorghum was calculated according to Chalk and Smith (1994):

$$\%Ndft = \left(1 - \frac{atom\%N^{15}excess_{agroforestry}}{atom\%^{15}Nexcess_{monoculture}}\right) \times 100 \quad (3)$$

The total amount of N transfer was determined analogous to equation (Equation 2).

Soil solution analyses

Ceramic suction cups were inserted at 1.2 m depth (see Lehmann et al. (1999a) for detailed description). Two cups were installed in each replicate; in the agroforestry system, they were inserted under the tree row and in the alley (2 m from the tree row). Vacuum was applied on individual sampling flasks by a portable electric pump and adjusted to the soil water suction obtained from tensiometers at the same site (Lehmann et al. 1998b). Soil solution was extracted 7 times in 1995 and two times in 1996 over a two week period at irregular intervals as long as it could be obtained from the cups before the soil dried up. Thus, only from May to September 1995 and June to July 1996 could the soil solution be sampled. Total inorganic N was analyzed spectroscopically with a Multi-Flow Analyzer (Alpkem) in separate samples. Soil solution samples were prepared for isotope analyses by drying.

Calculation of ^{15}N fluxes in the soil

To determine the ^{15}N fluxes in the soil, the soil water fluxes were calculated from soil water suction measurements with tensiometers at 0.45 and 1.5 m depths (see Lehmann et al. (1998b)). Leaching rates were obtained by using weekly measurements of the soil water suction, with the ^{15}N contents of the soil solution and soil physical parameters as described by Lehmann et al. (1999a). Due to insufficient retrieval of soil solution in one irrigation basin, the ^{15}N fluxes in the soil could only be given for two replicates.

The recovery of the applied ^{15}N in the soil could only be determined up to 0.9 m for which soil samples were available. For a full ^{15}N balance, however, the amount of ^{15}N up to 1.2 m depth was necessary, since the ^{15}N losses by leaching were measured at this depth. Therefore, the ^{15}N contents at 0.9–1.2 m depth from July 1996 were estimated by assuming the same enrichment as measured at 0.6 to 0.9 m. The true value should be between the presented values for 0–0.9 m and for 0–1.2 m. Both results are presented but only the values calculated with soil ^{15}N contents up to 1.2 m were used in the discussion.

Sample preparation and analyses

The leaf, branch and stover samples were gently rinsed with deionised water to remove adhering particles and dried at 70 °C for 48 hours. Afterwards, they were finely ground with a ball mill. Great care was taken to clean all containers during sample preparation to avoid cross contamination.

Soil samples were taken from 0–0.15, 0.15–0.3, 0.3–0.6 and 0.6–0.9 m depth at sorghum flowering in July 1995 and 1996. Composite samples of 8 subsamples were taken under the hedgerow and in the alley of the agroforestry system as well as in the sorghum monoculture with a purkhauer auger (25 mm diameter). The samples were air-dried and finely ground. All ^{15}N isotope samples were analyzed using an Elemental Analyzer (Carlo Erba NA 1500) for Dumas combustion connected to an isotope ratio mass spectrometer (FINNIGAN MAT delta E) via a split interface. For each sample type, i.e. soil, above-ground biomass, and soil solution, samples from control plots were analyzed which were not enriched with ^{15}N in order to calculate ^{15}N amounts in excess of natural abundance.

Statistical analyses

All nutrient data were compared by analyses of variance using a randomized complete block design. The effects of distance to the tree row were computed as split plot designs (Little and Hills 1978). In case of significant effects or interactions, individual means on the respective level were compared using LSD (Little and Hills 1978).

Results

The N input into the agroforestry system by biological N_2 fixation amounted to 3 to 15 kg N ha^{-1} at the different sampling times (Table 1). The proportion of fixed N was slightly higher in the branches than in the leaves of *Acacia saligna* (not significant), being 18 to 65% of the N in the branches and 8 to 29% of the N in the leaves. The total amount of fixed N in branches, however, was lower than in the leaves due to the lower biomass of branches compared to leaves (significant at $P < 0.1$). The proportion of fixed N increased from September 1995 to August 1996, but decreased thereafter in November 1996. The amount of N which was transferred from the leguminous tree to the intercrop in the agroforestry system was calculated as 54 kg ha^{-1} being 69% of the N in the sorghum after 1.5 years of cropping (Table 2).

The total ^{15}N recovery in plant and soil was found to be between 74 and 88% of the applied ^{15}N. Most of the ^{15}N remained in the topsoil (around 50% of the total soil ^{15}N, apart from the hedgerow position in 1995; Figure 2). However, the proportion of applied ^{15}N in 1995 was higher in the subsoil than the topoil under the hedgerow and sorghum as seen from the δ^{15}N values (Figure 2). Only around 10% were taken up into the above-ground biomass of both cropping systems. Seven times more ^{15}N accumulated in the *Acacia* hedge than in the sorghum

Table 1. Atom% ^{15}N excess of leaves and branches of *Acacia saligna* and *Senna* siamea, % N derived from biological N fixation and total amounts of N fixed; values within one column followed by the same letter are not significantly different at $P < 0.05$ (n = 3).

	atom% ^{15}N excess		%Ndfa^a[kg N ha^{-1}]		Ndfa^b		
	leaves	branches	leaves	branches	leaves	branches	total
Sept 95:							
Acacia saligna	0.193	0.203	28.7 a	31.6 ab	6.9 ab	1.6 b	8.5 ab
Senna siamea	0.285	0.269					
Aug 96:							
Acacia saligna	0.047	0.022	27.9 ab	64.4 a	9.2 a	6.1 a	15.2 a
Senna siamea	0.064	0.059					
Nov 96:							
Acacia saligna	0.043	0.039	7.5 b	17.8 b	2.0 b	0.6 b	2.6 b
Senna siamea	0.046	0.048					

[a] (Equation 1)
[b] (Equation 2)

Table 2. ^{15}N atom % excess, foliar N concentrations and N transfer in sole and mixed cropping systems with *Acacia saligna* and *Sorghum bicolor* in August 1996; values within one column followed by the same letter are not significantly different at $P < 0.05$ ($n = 3$).

	biomass [Mg ha^{-1}]	N content [mg g^{-1}]	atom% ^{15}N excess	%Ndft[a]	Ndft[b] [kg N ha^{-1}]
Sorghum monoculture	6.6	16.8	0.1367 a		
Sorghum alley cropped	5.3	17.6	0.0426 b	68.8	54.2
Acacia alley cropped	3.8	26.1	0.0470 b		

[a] (Equation 3)
[b] (Equation 2)

planted in the alley. Throughout the whole experiment the ^{15}N uptake by the trees was significantly higher than that of the intercrop ($P < 0.05$; Figure 3). Only 3 and 6% were calculated as N lost by leaching in the monoculture and the agroforestry system, respectively. In the alley cropping system, leaching losses were 60% lower under the hedgerow than in the alley.

Discussion

Biological N_2 fixation

The central assumption of the ^{15}N isotope dilution method is that both the leguminous plant and the reference are utilizing a soil N source with the same ^{15}N-to-^{14}N ratios (Witty 1983). An indication for this fact may be given if the leguminous tree and the reference tree have similar above-ground N accumulation dynamics and N uptake from the same soil N pool (Danso et al. 1993) for which a similar root distribution may serve here as a criteria. The root length distribution of *Acacia saligna* was similar to that of *Senna siamea* as seen from Figure 4. Additionally, the above-ground N accumulation was not significantly different between *Acacia* and *Senna* in April 1996 (32.1 and 37.6 g N tree^{-1}, respectively; $P > 0.05$). Although these results indicate that the requirements for application of the ^{15}N dilution technique to estimate biological N_2 fixation are likely to be met, they do not present a complete assurance for the validity of the underlying assumptions. Changes of soil ^{15}N availability with time may greatly affect fixation estimates and invariably occur after a one-time ^{15}N application (Witty 1983). Especially with low estimates of biological N_2 fixation, the ^{15}N dilution technique is subject to large errors (Boddey et al. (1995), Danso et al. (1993), Hardarson et al. (1988)).

The proportions of N derived from N_2 fixation were in the range of results from other studies of alley cropping systems with *Gliricidia sepium* in the Philippines (37%; Ladha et al. (1993)) or in Sierra Leone (19–71%; Amara et al. (1996)). The low total Ndfa compared to other alley cropping systems (Palm 1995) can be explained by the low biomass production due to wide tree spacing. The lower %Ndfa in the dry season in November 1996 compared to the previous sampling dates may be explained by a lower nitrogenase activity during periods of water stress (Srivastava and Ambasht 1994). The soil water availability was generally higher during the first rainfall maximum from April

Table 3. Nitrogen balance (% of applied ^{15}N) of the agroforestry system with *Acacia saligna* and *Sorghum bicolor* and of the sorghum monoculture after 1.5 years of cropping; values in one row followed by the same letter are not significantly different at $P < 0.05$ ($n=3$).

^{15}N flux	agroforestry			sorghum
	whole system	tree row	alley	monoculture
application	100	100	100	100
plant uptake	9.7	8.4 ab	1.3 a	10.9 b
leaching beyond 1.2 m	5.5	3.0	8.1	3.1
soil contents 0-0.9 m	51.2	51.9 a	50.5 a	64.8 a
recovery	66.4	63.3	59.9	78.8
soil contents 0–1.2 m	59.2	60.8	57.5	74.4
recovery	74.4	72.2	66.9	88.4

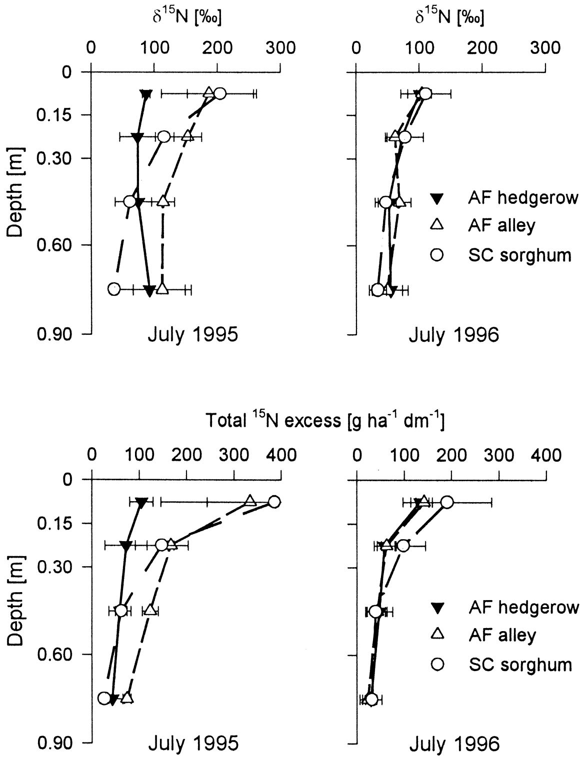

Figure 2. Distribution of ^{15}N in the soil under and between hedgerows of *Acacia saligna* (AF) and under sole cropped *Sorghum bicolor* (SC) in July 1995 and 1996; means and standard errors (n = 3).

to June than from October to December (compare Figure 1 and Lehmann et al. (1998b)). A reduction of the N_2 fixation estimates due to isotope discrimination against the heavier ^{15}N under water stress (Ledgard 1989) did not seem likely to happen with the enrichment method.

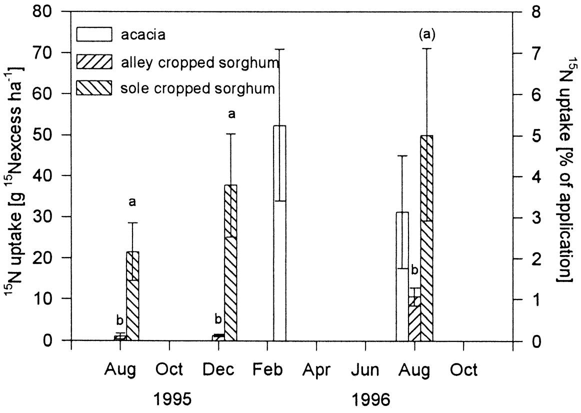

Figure 3. ^{15}N uptake and percentage recovery by sole and alley cropped *Sorghum bicolor* and alley cropped *Acacia saligna* (leaves and branches) from January 1995 to August 1996; bars with different letters are significantly different at $P < 0.05$ (in brackets at $P < 0.1$); means and standard errors (n = 3).

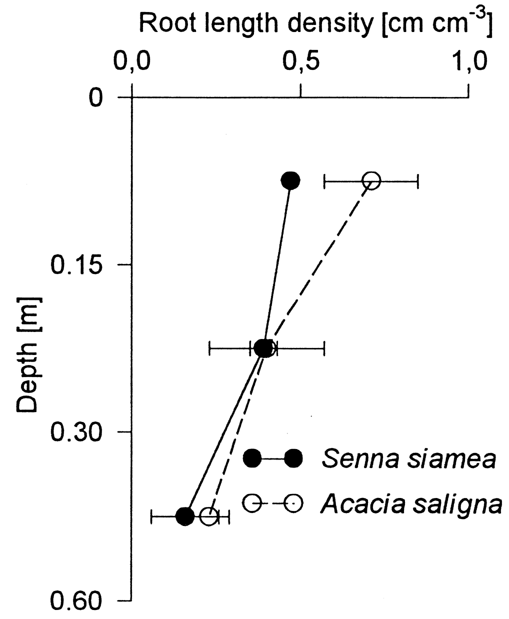

Figure 4. Root distribution of *Acacia saligna* and *Senna siamea* in November 1996; means and standard errors (n = 3).

Tree-crop interactions

The great importance of below-ground N transfer from leguminous trees to crops was frequently hypothesized (Sanginga et al. 1995) but only indirectly proven in agroforestry until now. In Costa Rica, Haggar et al. (1993) could not explain the observed N benefits from alley cropping maize and *Gliricidia sepium* with a N recovery from pruning applications. The mulched N accounted only for 15% of the N benefit from alley cropping. The authors concluded that the maize was taking up N which was released below-ground by the hedges. Results from Sanginga et al. (1988) also indicated that N from roots and nodules of preceding *Leucaena leucocephala* contributed to maize grain yield equivalent to an addition of 32 kg N ha^{-1}.

The higher percentage of N derived from transfer (69%) in the sorghum than actually fixed N in the acacias (28 and 64% in leaves and branches, respectively, in August 1996) does not follow the rational that the intercrop used the fixed N of the legume. The N transfer calculation using equation (Eqn. 3), as it was demonstrated for herbaceous legumes

(Chalk and Smith 1994) seemed not to be suitable for the studied tree-crop association. The higher calculated transfer of fixed N than biological N_2 fixation might have ecological reasons: (1) roots may have a higher % Ndfa than the leaves as shown by Ndoye et al. (1995) in a pot experiment with different leguminous trees, and only the leaves were analyzed in our study; and (2) pruning the trees may have led to a large input of fixed N from the rhizosphere due to root mortality (Nygren and Ramirez 1995). Most likely, however, the central requirement for the quantification of N transfer was not met, i.e. that the plant N uptake from soil N (as opposed to legume N) must have the same ^{15}N enrichment in the agroforestry system and in the monoculture. Strong indications for a failure to do so were the competition between tree and crop, since (i) the trees acquired more ^{15}N than the crop in the agroforestry system (Figure 3), and (ii) the topsoil ^{15}N stocks under the tree row were lower than in the alley and in the sole cropped sorghum in July 1995 (Figure 2). Additionally, the root distribution of the sorghum was deeper in monoculture than when associated with the trees (Lehmann et al. 1998b), probably taking up soil N with different isotope ratios as the soil ^{15}N contents decreased with depth (Figure 2). Therefore, the ^{15}N dilution method was not suitable for quantifying or even showing the existence of N transfer in the studied tree-crop association under field conditions due to the spatial variability of the ^{15}N labeling caused by a redistribution of the isotope. Viera-Vargas et al. (1995) also found unexpectedly high estimates of N transfer from a herbaceous legume to associated grass, which was explained by the utilization of different ^{15}N pools in monoculture and in association. In the cited study, the grass was more competitive than the legume and had a different uptake pattern when intercropped.

The redistribution of soil ^{15}N may have also affected the estimates of biological N_2 fixation of the acacias. If the soil ^{15}N enrichment is horizontally not equally distributed, the main requirement of the ^{15}N dilution methodology for the determination of biological N_2 fixation is not met. ^{15}N applications at several dosages (Viera-Vargas et al. 1995) or with slow releasing gypsum pellets (Witty 1983) may help to overcome some of the temporal variability of soil ^{15}N availability, but may not completely override the spatial variability in the hedgerow intercropping system (Figures 2 and 3).

In the hedgerow intercropping system, most of the applied ^{15}N was taken up by the trees and the crop ^{15}N uptake was significantly lower than in the sorghum monoculture ($P < 0.05$). However, this high competition for applied N was not reflected by a lower N nutrition or crop yield of the alley cropped sorghum in comparison to the monoculture (Lehmann et al. 1999b). Rather, the higher ^{15}N uptake by the tree than the crop was a horizontal redistribution of applied ^{15}N in the cropping system.

Nitrogen balance

The plant ^{15}N uptake was very low with only 10% of the applied ^{15}N after 1.5 years. Most of the ^{15}N was probably immobilized in soil microbial biomass and soil organic matter or adsorbed to mineral clay surfaces and therefore retained in the topsoil. Also, very little ^{15}N was leached beyond 1.2 m depth. The soils at the experimental site were highly N deficient and surface applied ammonium may not percolate through the soil profile in large amounts. Additionally, the high evaporation rates led to low water percolation below 1.2 m depth (<50 mm 100 days^{-1}; Lehmann et al. (1999a)). However, the ^{15}N leaching values were still in the range of plant uptake and therefore a relevant loss.

The lower ^{15}N leaching under the hedgerow than in the alley indicated a better nutrient capture by the trees than the intercrop. In the alley, the leaching losses were even six times higher than the plant uptake, whereas the trees took up three times more ^{15}N than the amount lost by leaching under the hedgerow. However, the ^{15}N export by leaching under the acacias was not lower than in the sorghum monoculture. The similar total leaching losses from the tree-crop association and the crop monoculture were in contrast to the results of the total N fluxes which were 47% lower in the agroforestry system than in the crop monoculture (Lehmann et al. 1999a). ^{15}N recycling by the trees from below 1.2 m depth cannot be excluded and may have caused the higher ^{15}N leaching values in the agroforestry system than the sorghum monoculture, also indicated by its higher proportion of ^{15}N in the subsoil in 1995 (Figure 2).

12 to 26% of the applied ^{15}N could not be accounted for in the agroforestry system and the sorghum monoculture, respectively. One reason may be that the measurements of the leaching rates were inaccurate. Under runoff conditions, macropores may

play an important role for the transport of nutrients in aggregated soils, which cannot be accounted for with the applied methodology (see also Lehmann et al. (1999a)). More likely was a gaseous loss of N. We found low N_2O losses with less than 0.1 kg N ha^{-1} during one cropping season at the same site (Wulf et al. 1999). Ammonia volatilization, however, may have been an important process of gaseous N loss, since the N was applied as soluble ammonium sulfate to a soil with a high pH of above 8 (Wild 1988). Gaseous N losses of 12 to 26% of the applied ammonium were lower than losses reported from lowland rice production systems with 30 to 60% of applied N fertilizer (Wild 1988).

Conclusions

The biological N_2 fixation estimates have to be regarded with caution, since a large vertical redistribution of the applied ^{15}N occured due to tree ^{15}N uptake and recycling. This redistribution led to unequal sources of soil ^{15}N, therefore violating the assumptions of the ^{15}N dilution technique. The higher calculated proportion of N transfer to the sorghum than biologically fixed N in the *Acacia* clearly demonstrated the limitations of this approach in hedgerow intercropping under field conditions.

Total ^{15}N uptake in above-ground biomass and leaching of applied ^{15}N was low in the dry tropical environment. Most of the ^{15}N was immobilized in the soil. Total plant uptake and leaching losses were not different in monoculture or hedgerow intercropping, only the distribution between tree and crop in the agroforestry system differed. The higher ^{15}N uptake by the trees than the intercrop indicated N competition, though without decreasing crop N nutrition. The vertical N redistribution is still not fully understood and further experimentation also assessing different soil N pools would help to identify sources and sinks of N in mixed cropping systems.

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